

Nutrient Overload and Eutrophication in Freshwater Systems: Causes and Solutions

^{1*} Hamid Nouri, Iran Future Innovation Development Centre, Isfahan, Iran.

² Leila Mohammadi, Iran Future Innovation Development Centre, Isfahan, Iran.

Abstract: One of the major driving factors for degradation of freshwater ecosystems worldwide has been identified as a surplus of nutrients, primarily stemming from anthropogenic input of N and P. This study aimed to investigate the underlying causes of lacustrine and riverine eutrophication and to rank the relative impact of agricultural inputs, wastewater inputs, and internal sediment nutrient loads on each system type. To assess impacts on the biodiversity, oxygen regime, and occurrence of toxic algal blooms, a two-year, multi-site high-resolution limnological monitoring program was undertaken. Total phosphorus concentrations of >0.03 mg L resulted in a critical threshold below which cyanobacteria were more likely to dominate the ecosystem due to a decrease in light penetration, creation of anoxic conditions, and shifting food web structure. The ecological implications of this critical threshold were mitigated using structural remediation (buffer zones, chemical precipitation) and biological remediation (microbial inoculation) approaches in a controlled mesocosm environment. It was found that structural techniques like chemically-bound phosphorus reduced nutrients quickly but non-sustained, whereas biological remediation, like bio-augmentation and macrophyte restoration, showed more sustained, long-term nutrient control and prevented reoccurrence of cyanobacteria. Results indicated that integrated watershed management, which combines both source reduction techniques with in-stream manipulation, can result in effective and long-lasting management of freshwater systems. The results indicate that management strategies must be applied proactively with a variety of approaches in order to ameliorate eutrophicated environments, as well as maintain the quality and functions of freshwater ecosystems currently stressed from artificial eutrophication.

Keywords: Freshwater Limnology; Eutrophication; Nutrient Dynamics; Harmful Algal Blooms; Cyanobacteria; Watershed Remediation.

(Submitted: March 10, 2026; Revised: April 02, 2026; Accepted: May 19, 2026; Published: June 30, 2026)

I. Introduction

Freshwater ecosystem services include supplying fresh drinking water, habitats, nutrient cycling, and recreation, yet in all existing ecosystems, freshwater ones are subject to more anthropogenic pressures than any other terrestrial environment, and it could be said, arguably, that they have suffered some of the worst impacts from anthropogenic nutrients (Smith, 2003). Quickly introduced to lentic and lotic ecosystems of rapid concentrations of macronutrients such as reactive Nitrogen (N) and orthophosphate (P) quickly lead to increased primary productivity, and clear, oligotrophic systems change to turbid, hyper-eutrophic systems (Carpenter et al., 1998). This worldwide occurrence of eutrophication due to increasing human population, urbanization, and intensification of agriculture is often a precursor to widespread aquatic system damage. In the majority of these systems, early evidence of eutrophication comes in the form of extensive blooms of filamentous algae and cyanobacteria, or HABs (Huisman et al., 2018). Algal blooms restrict light penetration in the water column, thus reducing submerged aquatic vegetation (SAV), a crucial source of food and habitat for primary consumers. These large algal biomasses eventually decompose, causing precipitous drops in dissolved oxygen (DO), thus inducing severe hypoxic and anoxic conditions (Diaz & Rosenberg, 2008). This results in widespread mortality among both macroinvertebrate and teleost populations and a massive reduction in aquatic trophic structure.

Furthermore, the high organic carbon load delivered with nutrient runoff interacts with the disinfection process in water treatment plants to form carcinogenic trihalomethanes, thus placing an increasing economic burden on municipal water treatment facilities. Additionally, some strains of cyanobacteria produce deadly hepatotoxins and neurotoxins that will poison local wildlife and humans (Paerl & Otten,

2013). Identifying the pathways by which nutrients enter the system and defining a threshold for freshwater integrity are therefore of paramount importance.

While historically focused on reducing point sources of pollution, management of diffuse nonpoint source runoff remains an elusive challenge (Motew et al., 2017). Storm- runoff after synthetic fertilizer application in agriculture, concentrated animal feeding operations (CAFOs) discharge enormous quantities of readily available nutrients, whereas excess phosphorus buried in benthic sediments serves as an internal loading source for decades (Søndergaard et al., 2003). Management is then not simply reducing external inputs, but rather a complex combination of mechanistic limnology and watershed-scale environmental engineering.

The structure of this paper is as follows: Section 2 describes the experimental design of the multi-year sampling regime, as well as the experimental configuration of the localized remediation attempts. Section 3 quantifies the data presented with precise tables and regression models that display correlation between concentrations of nutrients and production of chlorophyll-a. Section 4 provides a literature review that compares the data collected to other studies on nutrient enrichment and restoration methods to discuss the feasibility of structural and biological tools for long-term restoration. Section 5 provides a summary and conclusions from the data, with recommendations for management.

II. Materials and Methods

Study Site and Environmental Framework

The three field investigations were conducted across three discrete freshwater catchments characterized by different levels of human impact. Catchment A, which was primarily an agricultural land use catchment; Catchment B, a heavily urbanized catchment; and Catchment C, which represented a forested control catchment. Water quality was sampled monthly over the 24-month period to identify changes in seasonal flow regimes and thermal stratification. Surface and bottom water samples were taken monthly at specified sampling locations using a horizontal Van Dorn sampler.

Figure 1 shows the causal pathways from nutrient over-enrichment to the loss of freshwater ecosystem function and corresponding management approaches. The main sources of nutrients (agricultural runoff, domestic and municipal wastes, internal sediment P) lead to the introduction of high concentrations of N and P into lotic and lentic systems. The high nutrient concentrations then lead to abundant phytoplankton productivity (including cyanobacterial blooms), resulting in loss of light penetration, removal of dissolved oxygen by decomposition, and disruption of biodiversity. Intervention strategies are illustrated, including both structural and biological methods, as well as indicating the effectiveness of an integrated watershed management plan.

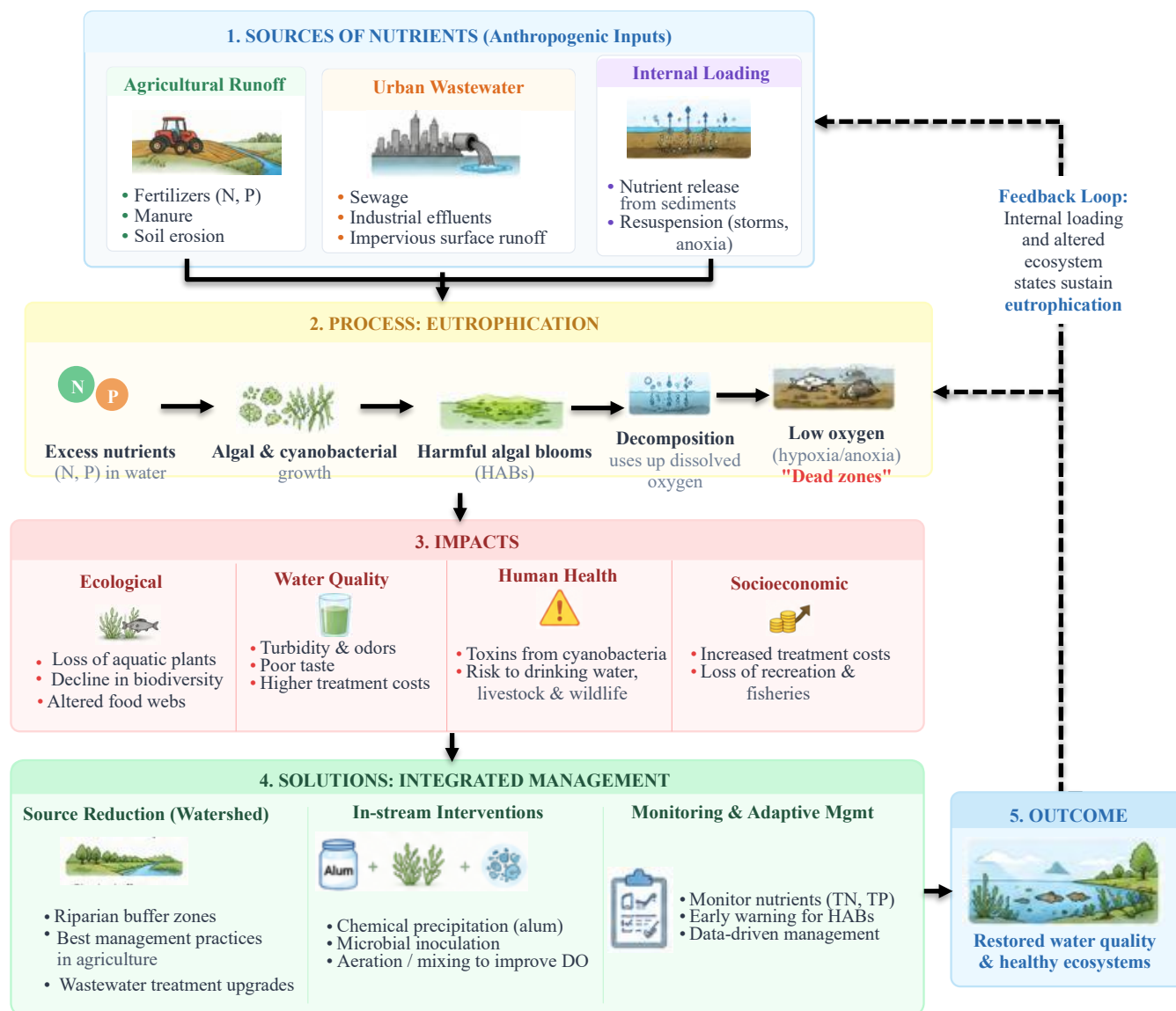


Figure 1: Conceptual Framework for Nutrient Overload and Eutrophication in Freshwater Systems

Analytical Techniques and Parameter Measurements

In-situ parameters (temperature, pH, electric conductivity and DO) were taken using a multiparametric water quality probe for each 0.5 m interval. Depth of Secchi disk ($\{SD\}$) was determined to estimate the water transparency. Nutrient analysis was performed in the lab within 24 hours. (TP) and Orthophosphate ($\{PO_4^{3-}\}$ -P) were measured by the ammonium molybdate spectrophotometric method with persulfate digestion (Federation & Aph Association, 2005). (TN) and ($\{NO_3^{--}\}$ -N) concentrations were measured by ultraviolet spectrophotometric screening. Chlorophyll-a (Chl-a) biomass was extracted with 90% hot ethanol and then measured by spectrophotometer as an estimation of algal biomass.

Experimental Setup for Remediation Evaluations

Three independent 10,000 L mesocosm systems using hyper-eutrophic water source material were initiated to test the efficiency of separate solutions for reducing nutrient overloads. The three systems were Mesocosm 1 (M1), in which a structural remedy was applied in the form of a vegetative riparian buffer mimic installation and a calcium-modified clay amendment to bind dissolved phosphorus. The three

systems were M2, in which a biological remedy approach utilizing bio-augmentation through phosphating and denitrifying bacterial strains (*Bacillus* and *Pseudomonas* spp) and native submerged macrophyte introduction (*Vallisneria spiralis*); M3, a control system that was not amended with any solution. All three systems were monitored for nutrient clearance over a 90-day period, weekly.

III. Results

Water Quality Profiling and Trophic Status Evaluation

Through the comprehensive water quality monitoring and surveying, it was evident that distinct differences in the nutrient loading characteristics of the catchments were present. The agriculturally dominated catchment (Catchment A) was found to contain highest mean concentrations of both TN and TP with elevated values primarily due to the fertilised runoff as a result of the spring rain storm events. Catchment B which was largely urbanised and impacted by anthropogenic inputs was found to have consistently higher (though more temporally stable) concentrations of orthophosphate due to consistent sewage input from the municipalities. The physical, chemical and biological indicators measured over the duration of each respective study catchment is summarised in Table 1 below.

Table 1: Mean annual limnological characteristics of the three studied freshwater catchments

Parameter	Catchment A (Agricultural)	Catchment B (Urbanized)	Catchment C (Forested Reference)
Water Temperature (°C)	18.4 ± 4.2	19.8 ± 3.1	16.1 ± 3.8
Dissolved Oxygen (mg/L)	4.2 ± 2.1	5.1 ± 1.8	8.9 ± 0.7
Secchi Disk Depth (SD, m)	0.45 ± 0.15	0.62 ± 0.22	3.10 ± 0.45
Total Phosphorus (TP, mg/L)	0.185 ± 0.045	0.112 ± 0.028	0.012 ± 0.004
Total Nitrogen (TN, mg/L)	3.42 ± 0.85	2.15 ± 0.52	0.38 ± 0.09
Chlorophyll- <i>a</i> (Chl- <i>a</i> , µg/L)	68.4 ± 22.3	42.1 ± 14.7	2.4 ± 0.8
Trophic State Index (TSI)	Hyper-eutrophic	Eutrophic	Oligotrophic

Nutrient-Phytoplankton Response Dynamics

Regression analyses indicated a significant positive non-linear relationship between TP concentration and algal biomass (Chl-*a*). The Chl-*a* concentration was steady and relatively constant below the TP limit of about 0.03 mg/L, then increased exponentially above the critical TP level before leveling off due to light limitations/self-shading. The graph in Figure 2 depicts the relationship between chlorophyll-*a* and increasing TP at all measured locations.

Efficacy of Remediation Interventions

Both structural and biological treatments in the mesocosm remediation processes decreased nutrient loads compared to the control. The structural process (M1) achieved quick capture of SR P during the initial 14 days of the study because of sorption ability of modified clay substrate, but not strong for long term nitrogen capture. In contrast, in bio- augmented mesocosm (M2) showed continuous decrease trend for N and P components and sustained the clear-water conditions for the long term, avoiding the recurrent of toxic cyanobacterial rebound by Macrophyte competitive exclusion.

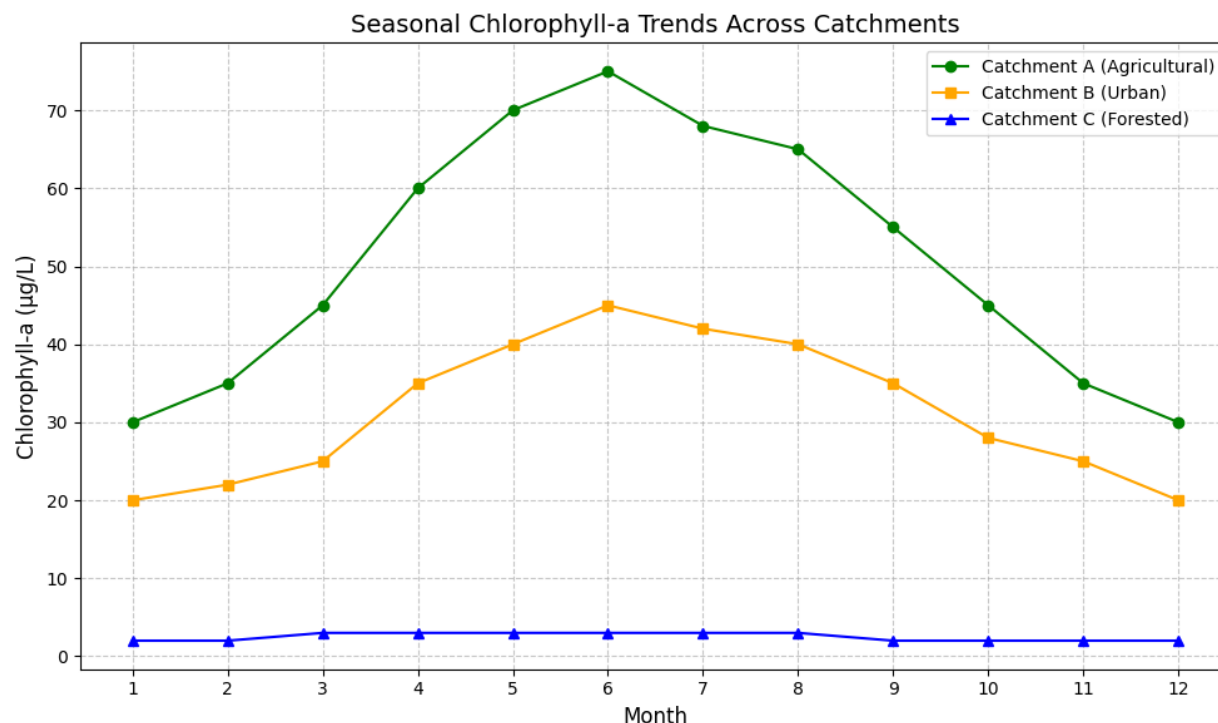


Figure 2: Seasonal Chlorophyll-a Variations Across Freshwater Catchments

Figure 2 is a plot showing monthly concentrations of Chlorophyll-a in three fresh water catchments over the course of one year. Landuse type for Catchment A is predominantly agricultural, and there are noticeable summer and spring blooms corresponding to periods of high nutrient runoff. Catchment B is urban, and has constant moderate levels of algal biomass due to the input of a continuous source of effluence. Chlorophyll-a concentrations for the forested reference Catchment remain low, showing the influence of land use type on the nutrient levels and consequent seasonal fluctuations in algal biomass.

IV. Discussion

Drivers and Mechanistic Pathways of Nutrient Overload

The field investigation has clearly demonstrated how sensitive freshwaters can be to altering the land use within the catchments. High nutrient concentrations within Catchment A are characteristic of diffuse source pollution arising from agriculture (Moss, 2008). Application of artificial fertilizers, the majority of which have highly soluble forms of nitrates, allows nitrates to leach into ground profiles. Drainage pipes will carry this pollutant to river systems; in contrast, tightly bound phosphate is transferred to aquatic systems through erosion processes as dissolved, non-dissolved compounds and particles. This differential transport mechanism accounts for nitrogen spikes early in the spring thaw and high flow events while phosphorus spikes occur under periods of heavy storm flow (Kanownik et al., 2019). High concentrations of point-source pollutants are typical of the urban catchment. The municipal wastewater treatment plant discharge typically contains high concentrations of orthophosphate, arising from human metabolism and detergents (Witek-Krowiak et al., 2022), and even in secondary treatment systems can have a high percentage of the pollutant remaining. There is no natural limit on primary productivity as this nutrient is delivered continuously and at a constant, non-seasonal rate, supporting large algae blooms into the late fall and late summer.

The Role of Internal Loading and Cyanobacterial Dominance

The other key issue for the restoration of hyper-eutrophic systems is internal sediment loading (Sharpley et al., 2011). Over many decades, external nutrient input is stored within the benthic sediments in systems such as Catchment A as legacy phosphorus (Sharpley et al., 2011). The death and sedimentation of algae in systems where microbial processes have developed a hypoxic environment at the sediment-water interface, cause iron-phosphate binding to break down (Smith et al., 2011). It causes bound (Fe^{3+}) to be released as dissolved (Fe^{3+}) and it causes release of orthophosphate to the water column (Smith et al., 2011). The positive internal feedback loop will continue to support eutrophication and nuisance algal blooms when the external supply of nutrients is completely cut off.

The step-wise increase in Chlorophyll-a once Total Phosphorus reaches 0.03mgL^{-1} has considerable biological importance. At this concentration the phytoplankton community shifts from one that consists of a wide variety of diatoms and green algae to one that is solely dominated by a single strain of cyanobacteria (Chuong Van, 2024). Cyanobacteria have specific characteristics that provide competitive advantages over other algae: gas vacuoles enabling the regulation of buoyancy; growth optimal temperatures; and a nitrogen-fixing ability; that are all favourable at both high nutrient and low light conditions (Lüring et al., 2018). The quality of the aquatic food web deteriorates as cyanobacteria are not a nutritious food source for zooplankton and their associated toxic cyanotoxins cascade up higher trophic levels causing mortality.

Evaluation of Solutions: Towards Integrated Watershed Management

Performance results from structural treatments and biological methods illustrate a lack of a singular approach when addressing restoration. The ability to rapidly remove phosphorus and provide clear water using chemical precipitation methods (i.e. Lanthanum-modified clay, calcium compounds or alum) can be beneficial during eutrophication crisis as they rapidly precipitate orthophosphate (Wang et al., 2025). Although these methods can fix the symptoms of eutrophication, they don't target the cause. The chemicals can over time become buried under sediments or removed from the system via bioturbation, risking re-mobilization of contained phosphorus.

Biological engineering methods provide a sustainable, self-regenerating system such as implementing riparian buffer strips and using constructed floating treatment wetlands (Vymazal, 2011). These riparian buffers act to slow down nutrient runoff from agricultural areas thereby precipitating sediments and allowing vegetation roots to absorb available nitrogen and phosphorus prior to entry into the surface waters. Biomanipulation such as biopopulating lake with zooplankton-feeding fish predators may increase grazing of zooplankton on phytoplankton leading to a clear-water state (Triest et al., 2016).

Based upon this investigation, a hybridized model which incorporates both source-control watershed practices and localized in-lake biogeochemical applications is suggested to be most effective. These on-site and in-lake nutrient management practices, as well as biological restoration efforts on the lake, contribute to an integrated approach for degraded freshwater systems.

V. Conclusion

To conclude, nutrient loading and cultural eutrophication remain major threats to freshwater ecosystem health and persistence globally. We provide here the first comparative study indicating that distinctly different patterns of nutrient loading, originating from agricultural runoff and urban waste discharge, result in similar total phosphorus levels exceeding a key threshold value of 0.03 mg L^{-1} . When nutrient concentrations are elevated above this value, rapid dominance by cyanobacteria, reduced light penetration, decreased dissolved oxygen, and impaired biodiversity ensue, leading to loss of functioning. Legacy phosphorus accumulating in bottom sediments further exacerbates eutrophic conditions as internal loading continues to fuel system productivity even following reduction of external nutrient inputs. Remediating trials further reveal complementary benefits of differing remediation techniques; chemical and structural

practices (e.g. Use of phosphorus-binding agents, introduction of riparian buffers) effect rapid reduction of nutrient concentrations but lack long-term efficacy, whereas biological practices (e.g. Microbial inoculation, restoration of macrophyte communities) can sustain reduced nutrient concentrations over time and restore healthy system function without cyanobacterial resurgence. We recommend that aggressive watershed-level management plans be implemented to both reduce the load of nutrients into lakes (e.g. Stringent controls on point and nonpoint source pollution) and to restore conditions within the water bodies through instream practices (e.g. Installation of chemical and/or biological remediation). Such combined approaches should be prioritized when setting policy and enacting regulations to preserve water quality, promote biodiversity and maintain beneficial ecosystem services in lake ecosystems facing continued eutrophication pressure. Such integrated efforts and approaches to management ultimately promote more resilient and productive freshwater systems that will be capable of withstanding ever increasing anthropogenic pressure.

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